Frost Protection in Orchards and Vineyards

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There is a chronic and large demand for low cost, effective and environmentally acceptable cold protection, also referred to as "frost" protection, techniques in temperate areas around the world to protect orchards (pome fruits, stone fruits, nut crops, citrus), vineyards, cut flowers, small fruits (berries), Christmas trees, Douglas fir seed orchards and numerous other crops against damaging cold temperature occurrences. Protection times include frosts in the spring and fall as well as severe winter freezes.

There are very few years when at least some frost protection is not needed in PNW fruit growing areas, but the systems must be maintained and kept fully operational every year. Because of the tremendous economic consequences of not protecting, producers in the region have installed one of the most extensive, elaborate, and expensive frost protection networks in the world.

Cold protection events in the PNW usually occur during "radiation" frost conditions when the sky is clear and there is little wind and strong temperature inversions can develop. These conditions can happen during spring, fall or winter, although most tree crop cold protection activities occur in the spring and are designed to keep buds, flowers and small fruitlets above the "critical" temperatures at which they can be killed. On the other hand, it is often necessary to frost protect PNW *vinifera* vineyards in the fall to prevent leaf drop so that new sugar will continue to accumulate in the berries. Sometimes it is required that protection measures be initiated during very cold temperature events during the winter period on perennial tree (i.e., peaches, apricots) and vine crops. Very often only a couple of degrees rise in air temperature is sufficient to minimize cold damage.

It sometimes seems as if <u>every</u> method of orchard frost protection that has ever been devised has been tried in the PNW. That's probably not the case, but it has been through this trial-and-error process that the large PNW frost protection network has and still is evolving. Many mistakes have been made as well as many successes. This presentation will discuss the current "state-of-the-art", some rules-of-thumb, general considerations and opinions on orchard frost protection in temperate areas like central Washington.

The Basics of Orchard Frost Protection

Any crop can be protected against any freeze if economically warranted. The selection of a frost protection system is primarily a question of economics. Fully covering and heating a crop as in a greenhouse are the best and also the most expensive cold protection systems, but they are usually not practical for large areas of orchards, vineyards and many other small fruit and vegetable crops, unless other benefits can also be derived from the installation. The questions of how, where, and when to protect a crop must be addressed by each grower after considering crop value, expenses, debt levels and cultural management practices.

There is no perfect method for field protection of crops against cold, but quite often combinations of methods are advantageous. However, the capacity of any system or combined systems will always be exceeded at some point. The best frost protection technique is good site selection! In

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addition, a well-maintained and calibrated frost monitoring (thermometers and alarms) network will always be required.

The objective of any crop frost protection system is to keep plant tissues above their **critical temperatures.** The critical temperature is defined as the temperature at which tissues (cells) will be killed. Critical temperatures will vary with the stage of development and ranges from well below 0°F in midwinter to near 32°F in the spring, and they are strongly influenced by general weather patterns for 7-14 days preceding the cold temperature event, day length and physiological stages. They are most commonly reported for the 10%, 50% and 90% mortality levels. Knowledge of the current critical temperatures and the latest weather forecast for air and dew point temperatures are important because they tell the producer how necessary heating may be at any stage of development and how much of a temperature increase should be required to protect the crop.

Protection against advective (windy) freezes is much more difficult to achieve than protection against radiative freezes (see Appendix A). Consequently, most of the methods/systems are practical and effective only under radiation situations. The formation of inversion layers is a benefit and many methods take advantage of an inversion to furnish, trap and/or recirculate heat.

A high dew point is probably the most powerful and effective mechanism available for reducing freeze damage to plants (see Appendix A). This is due to the "heat pump" effect which replaces radiation losses with the latent heat of condensation. Any frost protection method which increases the water vapor content of the air is generally beneficial (but this is very difficult to accomplish!). Heat from water is more efficient than some other sources because it is released at low temperatures, is less buoyant (no "stack" effect), and may selectively warm the coldest plant parts.

All frost/cold protection methods consist of one or more of the following principles:

1. Good site selection for adequate cold air drainage and proper siting of buildings, windbreaks and fences to ensure unrestricted cold air movement
2. Mixing of the air to use heat stored in the atmosphere and prevent stratification (e.g., wind machines, helicopters).
3. Direct convective heating of the air (e.g.., heaters, heated water undertree).
4. Radiant heating directly to plant (e.g.., heaters, undertree sprinklers).
5. Release of the latent heat of fusion (e.g.., freezing water directly on plant-overtree sprinklers; or on surface under the canopy-undertree sprinklers).
6. Release of the latent heat of condensation (e.g.., humidification, fogs, sprinkle).
7. Radiative heat loss interception (e.g.., fogs, covers).
8. Utilization of soil heat storage (e.g.., bare soils).
9. Thermal insulation (e.g.., covering foams, greenhouses).
10. Bloom delay (e.g.., overtree sprinklers and/or tree wraps and paint).
11. Planting cold hardy and/or late blooming varieties.
12. Genetic development of cold resistant plants.

Some basic descriptions of relevant frost protection terms and physical concepts are presented in Appendix A at the end of this paper. Please review this section if you are unfamiliar with some of the terminology used in the following discussion.

The final selection of an individual cold protection system will depend on the crop, location, soils, exposure, and personal preferences, as well as the economic considerations. The importance of good site selection cannot be over emphasized.

Artificial orchard and vineyard heating systems will supply anywhere from 0.5 to 7 million BTU/ac/hr. Economically it is not possible to protect against all frost situations which may occur, so the grower must decide what level of protection they need and can afford. These decisions must be based on local fruit prices plus the cost of the equipment and increased labor for frost protection activities. They must be balanced against the costs of lost production, possible long-term tree damage, and the amount of debt that must be repaid to lenders. The added capital cost for the equipment must be borne by the total added income generated by increased fruit yields and quality. In other words, is it worth it? In most cases because of the tremendous amount of capital that must be invested in competitive modern orchards and vineyards, the grower MUST have the best, most effective frost protection system(s) available. They cannot afford even one year's lost production

Costs of Frost Protection Systems

It is quite difficult to present representative cost figures for frost protection systems since the installations are site-specific. Table 1 presents some "ball park" estimates for complete installed frost protection systems not including land value. The addition of wells and/or ponds is not included since these costs are extremely variable. If two or more systems are used the costs are additive.

Table 1. Estimated initial costs of frost protection systems common to Washington orchards.

Method	Estimated Cost/ac
Wind Machine (10-12 acres)	$ 1,500 - $ 1,800
Overtree Sprinkler	$ 900 - $ 1,200
Undertree Sprinkler	$ 900 - $ 1,200
Overtree Covers	$ 10,000 - $ 15,000
Undertree Microsprinklers	$ 1,000 - $ 1,500
Return Stack Oil Heat (40/ac)-used	$ 400 - $ 450
-new	$ 1,000 - $ 1,200
Pressurized Propane Heaters	$ 2,500 - $ 4,000

Economic comparison of the annual operating costs of the various systems have not been done in recent years. However, Table 2 presents some estimates which were made in 1979 on cost/acre/hr basis.

Table 2. Estimated annual per acre/hour operating costs for frost protection systems in 1979.

Method	Estimated Costs/ac
Return Stack Oil Heaters	$ 20.04
Propane Heaters	16.31
Wind Machine	9.57
Sprinkling (utilized 100% for frost)	3.95
Sprinkling (utilized 20% for frost)	1.70
Frost-free site	0.00

While the price of oil has gone down somewhat and electricity has gone up since 1979, the relative values have probably not changed significantly in the interval. Land prices may be higher because of the demand for good orchard sites, however, the frost protection benefits of good site selection will repay the extra costs many times over the life of the orchard.

Frost Protection Methods and Systems

In selecting a system to modify cold air temperatures that may occur across a block, an orchardist must consider the prevailing climatic conditions which occur during the cold protection season(s). Temperatures and expected durations, occurrence and strength of inversions, soil conditions and temperatures, wind (drift) directions and changes, cloud covers, dew point temperatures, critical bud temperatures, tree or vine condition and age, land contours, and orchard cultural practices must all be evaluated. The equipment to be used must be simple, durable, reliable, inexpensive and non polluting. Timing is critical and the equipment must work every time!

The use of chemical sprays (e.g.. zinc, copper, etc) to improve frost "hardiness" of deciduous trees in the Northwest has been found to offer no measurable benefit in limited scientific investigations. Likewise, sprays to eliminate "ice nucleating" bacteria have not been found beneficial because of the great abundance of "natural" ice nucleators in the bark, stems, etc. which more than compensate for any lack of bacteria. Special "fogging" systems which produce a 20-30 foot thick fog layer have also not worked well because of the difficulty in containing and/or controlling the drift of the fogs and potential safety/liability problems if they crossed a road.

Overtree systems have been used for bloom delay (evaporative cooling in the spring) on apples and peaches in the spring which ostensibly keeps the buds "hardy" until after the danger of frost has passed. It does delay bloom, however, it has not been successful as a frost control measure on deciduous trees because water imbibition by the buds which causes them to lose their ability to supercool. This results in critical bud temperatures that are almost the same as those in non-delayed trees. In other words, although bloom is delayed, there is no delay in critical bud temperatures and, thus, no frost benefit.

Table 3. Approximate relative heat values of water and #2 heating oil.

Condensation of water at 32°F releases	9000 BTU/ US gal
Evaporation of water at 32°F absorbs	9000 BTU/US gal
Freezing (fusion) of water to ice releases	1200 BTU/US gal
10°F temperature change of water releases/takes	83 BTU/US gal
Oil (#2 Diesel) burning releases	142,800 BTU/US gal
Propane burning releases	91,500 BTU/US gal
40 oil heaters/ac @ 0.75 gal/hr/heater releases	4,284,000 BTU/ac/hr

Table 3 presents some relative heat values for oil and water. These show that a 0.08 ac/in/hr application of water releases a total of 2.6 million BTU/ac/hr, and 0.15 ac/in/hr provides 4.9 million BTU/ac/hr if it all freezes in both cases. A 40 heater/ac return stack oil heat system supplies about 4.3 million BTU/acre which can potentially raise the temperature as much as 6°F with a strong inversion. Unfortunately, current commercially available diesel oil and propane fired heating systems are only 10-15% efficient: 85-90% of the heat rapidly rises above the crop and is lost.

FROST PROTECTION WITH WATER

Frost protection with water can require large volumes of water to be available for short periods of time which often creates major physical and legal problems for growers. In addition, there may be significant cultural as well as environmental consequences.

Physically, there are problems because frost requires water deliveries before water is normally required for irrigation and many canal systems are not ready that early in the year. In addition, most of the canal and on-farm delivery systems in western US are generally designed to satisfy the requirements of furrow (rill) irrigation (max. delivery 6-9 gpm/ac continuous flow to farm's total cropped area) which is also adequate for standard sprinkle systems. These flows are usually combined and used to irrigate smaller areas ("sets"), often at rates above 100 gpm/ac (0.21 in/hr) and the water use is rotated over several days to cover the entire cropped area. This rate of water deliveries is much too low for frost protection over the same area so many growers are drilling wells and building large holding ponds for supplemental water or unused allocations. Table 4 presents a summary of water requirements for frost protection as well as overcrop evaporative cooling (EC) in the PNW.

Table 4. General recommended guidelines for individually designing various orchard sprinkle/microsprinkle systems on a total area covered basis (multipurpose needs are often additive).

	Overtree Frost 1/	Undertree Frost 2/	Irrigation	Overtree EC 3/
Average Application Rate, gpm/ac	≥70	≥40	≥8	≥40
Water Supply, hrs/week 4/	60-80	50-70	25-160	60-100
Chemical injection	NO	NO	Sometimes 5/	Usually 5/
Water Treatment 6/	Screens	Screens	Screens, Filters	Screens, pH 7/
Water Quality	Marginal Concern	Marginal Concern	Major Concern	Major Concern
Uniformity (UCC)	≥80%	≥70%	≥70	≥80%
Cycling?	NO	NO	OK	YES

1/ Not recommended for stone fruits. Never use with wind machines.
2/ Can be used with wind machines and/or heaters to supplement.
3/ Evaporative Cooling. A separate overtree water application system is often appropriate.
4/ Water supply to cover the time period it is required.
5/ Make sure injected chemicals are compatible, must follow labeling, and that all required chemigation safety devices are installed.
6/ Chemical and/or biological control (eg. chlorine) treatment will usually be required for low volume, small orifice systems used for irrigation (eg. drip/micros) and/or undertree microsprinkle frost.
7/ pH control ≥ 6.5 usually required for ALL overtree evaporative cooling (EC) in central Washington.

The water must be kept free of debris by screens or other methods to prevent sprinkler heads from plugging with disastrous results. The water delivery system must be well maintained and it must work every time without exception and without breakdowns.

Legally, growers may have problems amending existing water rights or obtaining new water rights to groundwater for frost protection purposes. While there is little doubt that using water for frost protection in orchards is an economically beneficial use of that resource since it can mean the difference between a crop and no crop, many areas are having difficulty with the state water authorities and courts recognizing that concept.

Water applied for frost protection potentially affects several critical cultural factors including fruit quality, disease, and pests. Environmentally, the water is applied in large amounts at times when the trees are using very little water resulting in groundwater contamination by leaching of chemicals and nutrients from saturated soils.

Overtree Sprinkling

Overhead or overtree sprinkling is the field system which provides the highest level of protection, and it does it at a very reasonable cost. However, there are several disadvantages and the risk of damage can be quite high if the system should fail in the middle of the night. It is the only method that does not rely on the inversion strength for the amount of its protection and may even provide some protection in advective frost conditions with proper design. Many of these systems may have a triple purpose: irrigation, frost protection and evaporative cooling (EC) for color and sun scald reduction (on apples).

Some tree species/cultivars (e.g.. stone fruits) may not be able to support the ice loads and applications cannot be interrupted during the frost period. It requires large amounts of water, large pipelines and big pumps. It is often not practical because of water availability problems. In addition, some growers have reported problems with calcium and silicon carbonate precipitates on the fruit resulting in increases packing costs since the deposits must be removed.

Generally, adequate levels of protection require that 70 to 80 gpm/ac (0.15-0.18 in/hr) of water (on a total area basis) be available for the duration of the heating period. "Targeting" overtree applications to just the tree canopy (e.g.. one microsprinkler per tree) can reduce overall water requirements down to about 50-55 gpm/ac, but the water applied <u>on the tree</u> is still ≥ 0.15 in/hr. Protection under advective conditions may require application rates greater than 100 gpm/ac depending on wind speeds and temperatures. The entire block or orchard must be sprinkled at the same time when used for cold protection.

The amount of protection from overtree sprinkling depends only on the amount (mass) of water applied.

The application of water to the canopy must be much more uniform than required for irrigation so that no area receives less than the designated amount. A uniformity coefficient (UCC) of not less than 80% is usually specified. The systems for frost protection must be engineered for frost protection from the beginning. Mainlines, pumps and motors (3-5 BHP/ac) must be sized so that the entire orchard or block can be sprinkled at one time. A separate, smaller pump is often installed for irrigation purposes and the block watered in smaller sets. Sprinkler heads should rotate at least once a minute and should not permit ice to build up and stop the rotation and/or water application. Pressures should be fairly uniform across the block (e.g.., less than 10% variation).
Large amounts of water are required for overtree (and undertree) sprinkling, so many Washington orchardists are drilling wells and/or build large holding ponds for supplemental water. There are extra benefits to these practices in that the well water is often in excess of 65°F and the ponds tend to act as solar collectors and warm the water. If economically possible, growers will try to size the ponds to protect entire blocks for as much as 60-80 hours per week.

When applied water freezes, it releases heat (heat of fusion) keeping the temperature of an ice-water "mixture" at about 31-32°F. If that mixture is not maintained, the temperature of the ice-covered plant tissues may fall to the wet bulb temperature and could result in severe damage to the tree and buds. The applied water must supply enough heat by freezing to compensate for all the losses due to radiation, convection, and evaporation. Water should slowly but continuously drip from the ice when the system is working correctly. The ice should be relatively clear.

There may be an "evaporative dip" or a temporary drop in the ambient air temperature due to evaporative cooling of the sprinkler droplets when the sprinkler system is first turned on. The use of warm water, if available, can minimize the temperature dip by supplying most of the heat for evaporation. The recovery time and the extent of this dip is dependent on the wet bulb temperature. Table 5 shows recommended turn-on temperatures to the wet bulb temperature (slightly above dew point temperature) for cold water to reduce evaporative dip with overtree sprinkling.

Table 5. Suggested starting temperatures for overtree sprinkling for frost protection based on wet bulb temperatures to reduce the potential for bud damage from "evaporative dip" to keep plant tissues above about about 30°F.

Wet Bulb Temperature		Starting Temperature	
°F	**°C**	**°F**	**°C**
≥26	**≥ -3.3**	**34**	**1.1**
24 to 25	**-4.4 to -3.9**	**35**	**1.6**
22 to 23	**-5.6 to -5.0**	**36**	**2.2**
20 to 21	**-6.7 to -6.1**	**37**	**2.8**
17 to 19	**-8.3 to -7.2**	**38**	**3.3**
15 to 16	**-9.4 to -8.9**	**39**	**3.9**

Since the heat taken up by evaporation at 32°F is about 7.5 times as much as the heat released by freezing, at least 7.5 times as much water must freeze as is evaporated. And, even more water must freeze to supply heat to warm the orchard and satisfy heat losses to the soil and other plants. Evaporation is happening all the time from the liquid and frozen water. If the sprinkling system should fail for any reason during the night, it goes immediately from a heating system to a very good refrigeration system and the damage can be much, much worse than if no protection had been used at all. Therefore, when turning off the systems, the safest option on sunny, clear mornings is to wait (after sunrise) until the melting water is running freely between the ice and the branches. If the morning is cloudy or windy, it may be necessary to keep the system on well into the day.

Overtree sprinklersystems have been successfully used by Washington growers since the late 1940's, although most systems were installed in the early 60's. There was a period not long ago when overhead systems were being replaced in Washington with undertree systems due to disease (e.g.. Fireblight, Coryneum blight, and scab) rather than frost protection related problems. However, the loss of daminozide (Alar) and a shift to new varieties and orchard management systems has increased the risks of fruit sunscald ("sunburn") and inadequate color development. Consequently, grower interest and adoption of over-crop evaporative cooling as a feasible, environmentally acceptable technique has revived the use of these sprinklersystems on both new and old blocks.

Undertree Sprinkling

Another commonly used frost protection method in Pacific Northwest orchards is the application of water through undertree sprinklers. Research and experience has shown that the success of undertree sprinkler systems (used both with and without wind machines) is influenced by the following factors. These are (in approximate order of importance): 1.) the height and strength of the temperature inversion; 2.) the level of protection is directly proportional to the **amount** (mass) of water applied and the **temperature** of the applied water; 3.) the volume of air flow moving into the orchard (advection) which can remove about half the heat; 4.) release of latent heat from the freezing of the applied water (small contribution); and, 5.) radiation heat fluxes from the soil. Other important, but less significant, parameters are the height and type of cover crop and water droplet sizes. The relative contribution of any one factor will vary with site and existing climatic conditions at the time, but the currently expected maximum amount of temperature increase (at 6 ft) is about 3°- 4°F using cold canal water in the spring (depending on inversion strengths). Undertree systems are very compatible with wind machines and/or heaters (on borders) and the respective individual heat contributions appear to be additive up to a point limited by the resistance to heat transfer of the air. Many of the systems are being used in conjunction with wind machines. There are less risk, less disease problems and lower water requirements than overtree systems since the water does not come in contact with the buds.

The amount of protection from undertree sprinkler systems depends on both the amount (mass) of the water and the temperature of the applied water as limited by the strength of the thermal inversion.

Most of the systems use small (5/64"-3/32"), low-trajectory, ($\leq$ 7°) sprinkler heads at 40-50 psi. Applications range from 0.08 to 0.12 in/hr (40-55 gpm/ac) or a little more than half of overtree requirements. Sprinklers are usually turned on around 32°F, or earlier if dew points are low, in order to raise the humidity as much as possible and prevent freezing of the risers and heads.

The level of protection is very dependent on the amount of water applied, up to a maximum of about 50 gpm/ac, and the areal extent of the freezing surface. Part of the heat from the freezing and the cooling of water is carried into the ground by infiltrating water, part goes into warming the air, and part into evaporation (which slightly increases the humidity). It is estimated that at least 75% of the heat is lost with conventional undertree systems. If the water applications are not adequate, total heat losses can approach 100%. "Misters" and "micro-sprinklers" should work well for undertree frost protection <u>only</u> if the application rates and coverage are adequate. Small droplets and "fogs" do not compensate for the lack of adequate water applications in undertree systems.

The transfer of heat to the frosty buds is by radiation, convection and by any condensation which occurs on the coldest (radiating) plant tissues. The radiant heat and condensation (latent) heat have little effect on the thermometer, which may not accurately reflect the effective protection levels.

Previous studies have concluded that undertree sprinkler systems can be a good method of protecting orchards from frost if the grower only needs a few degrees of protection provided by a system that can also be used as an irrigation system. It is more economical and pollution-free than an oil heating system, and does not entail the dangers of limb breakage, disease, and sprinkler system failure of an overtree sprinkler system. The maximum estimated increase in air temperature was about 1.7°C (3°F) under central Washington conditions. The concurrent use of a wind machine has been found to add about an equal amount of temperature rise as was contributed by the undertree system, but this needs further validation.

It has been experimentally determined that almost all the heat measured in an undertree-sprinkled orchard under freeze conditions can be attributed to just the heat released by the water as it cools to wet bulb temperature (almost dew point temperatures). The contribution of freezing water in heating the air in undertree orchard frost protection is minimal, since much of the heat from the freezing of water is picked-up by water that is subsequently applied and infiltrates into the soil. In other words, since the freezing of water is ineffective in heating the air and most of the heating is supplied by the cooling of water droplets as they move through the air, the most logical improvement in the technology is to heat the water (e.g.., oil-fired flow through heaters, using warm groundwater or by solar heating of ponds) before distribution to the field, especially when water supplies are limited.
The warmer the water, the lower the average application rate required to achieve the same protection levels for a given inversion strength. In addition, many orchardists do not have availability to the large amounts of water required for adequate frost protection with undertree sprinklers (e.g., 40 gpm/ac or 0.09 in/hr [6.25 l $s^{-1}ha^{-1}$ or 2.3 mm hr^{-1}]) with cold canal water. Consequently, an economical heating system using low volumes of water coupled with an auxiliary means to heat the water supply would be a readily acceptable alternative for orchard and vineyard growers.

Use of Warm Water. Systems that heat the water have been tested in Washington and other areas and they have been shown to be a much more efficient use heating oil. These systems utilize large stationary boilers/heat exchangers at the side of the field and heats water for application through the existing undertree irrigation system. The heat is thereby uniformly spread over the orchard floor, and since the heat is applied at a much lower temperature than oil or gas heaters, much more of the heat stays within the orchard boundaries. Low application rates also reduces water logging of orchard soils and reduces leaching of nutrients and other chemicals towards the groundwater. Heat input can be quickly adjusted to match environmental conditions at a single point. Air pollution is also substantially reduced with a heat exchanger based frost protection system. Research has also shown that boiler/heat exchanger systems would work well in combination with wind machines.

Analysis indicate that the boiler/heat exchanger should be sized to produce about 0.75 to 1 million BTU's per acre per hour for PNW spring frost conditions (about 35-40 boiler horse power per acre). Generally, individual boilers with heat exchangers should be less than 800 HP because of size and cost considerations (each boiler covering 20-30 acres). Using a separate boiler/heat exchanger for every 20-30 acres also reduces conveyance heat losses. The cost of a new boiler/heat exchanger can range from $2,500 to $3,500 per acre although these systems (e.g., 800 BHP) can be seasonally rented (perhaps in combination with a mint still operation) for about $8,000-9,000.

Other Considerations for Undertree Sprinkling. Cover crops provide more freezing surface and insulation from the ground. They are apparently quite beneficial with undertree sprinkling and should be as tall as possible (12-15 inches) without interfering with the operation and throw patterns of the sprinkler heads.

Evaporative dips (as found on overtree systems) have not been observed when undertree sprinklers are first turned on, contrary to some information contained in the literature. This is apparently due to the fact that any heat absorbed by the evaporative cooling of the droplets comes directly from the water rather than the atmosphere.

The sequencing of blocks on laterals and other means of "stretching" water to cover more area is generally not recommended. The whole block should be irrigated continuously and the mainlines, pumps and motors sized accordingly. Trees should be trained so that the water does not reach any buds and flowers on the lower branches. Sprinkler risers should be maintained in a vertical position at all times.

The use of undertree sprinkling in conjunction with wind machines works well since heat from the inversion is supplied plus any heat and humidity from the sprinkling that rises above the canopy is captured recirculated back through the orchard. Contrary to the case of wind machines and heaters, sprinkler heads are not turned off around the fan since the amount of protection is dependent on the freezing surface area plus the type of heat released is not nearly as buoyant as the heaters (less "stack" effect). Finally, the water is usually turned on first and the wind machines later since the use of water is less expensive.

There are many misconceptions concerning the use of low volume sprinkler systems for cold temperature modification in orchards. The benefits of microsprinklers due to their small droplets and purported radiation-loss reducing "fogs" has often been misrepresented and many spurious claims have been made with respect to the level of protection. In most cases, the benefits which have been attributed to the presence of small droplets and fogs are actually occurring because of already high humidities present in the general air mass. The microsprinklers may not have even been necessary for protection in these marginal situations where the high dew points provides a heat source which greatly limits the rate of air temperature decrease.

Fogging which is sometimes observed with sprinklersystems is a result of water that has evaporated (taking heat) and condenses (releasing heat--no "new" heat is produced) as it rises into cooler, saturated air. As the "fog" rises, into ever colder and unsaturated air, it evaporates again and disappears. The duration of fogs or mists will increase as the ambient temperature approaches the dew point temperature. Thus, the "temporary" fogging is a visual indicator of heat loss that occurs under high dew point conditions and does not represent any heating benefit. It has been shown that the droplet size has to be in the range of a 10 micron diameter to be able to affect radiation losses, and the smallest microsprinklerdroplets are at least 100 times larger.

OTH ER COMMON FROST PROTECTION METHODS

Heaters

Fossil-fueled heaters were once the mainstay of PNW orchard cold protection activities but fell into disfavor when the price of oil became prohibitive and other alternatives were adopted. They have made a minor comeback in recent years, particularly in soft fruits and vineyards where winter cold protection may be required, but are plagued by very low heating efficiencies and rising fuel costs.

Unfortunately, 75-85% of the heat may be lost due to radiation to the sky, by buoyant convective forces above the plants ("stack effect") and the katabatic wind drift (a big problem with all frost protection systems except overtree sprinkling) moving the warmed air out of the orchard. Any practice that reduces these major losses will increase the effectiveness of the method. If most of the heat released by combustion could be kept in the orchard, then fossil fuel heating for cold protection would be very effective and economical.

Heaters are “point” applications of heat. If all the heat released by combustion could be kept in the orchard, then heating for cold protection would be very effective and economical. Unfortunately, however, 75-85% of the heat may be lost due to radiation to the sky, by convection above the plants ("stack effect") and the wind drift moving the warmed air out of the orchard. Combustion gases may be 1200°F to over 1800°F and buoyant forces causes most of the heat to rapidly rise above the canopy to heights where it cannot be recaptured. There is some radiant heating but its benefit is generally limited to adjacent plants and only about 10% of the radiant energy is captured. New heater designs are aimed at reducing the temperature of the combustion products when they are released into the orchard or vineyard in order to reduce buoyancy losses.

Many types of heaters are being used with the most common probably being the cone and return stack oil burning varieties. Systems have also been designed which supply oil or propane through pressurized PVC pipelines, either as part of or separate from the irrigation systems. Currently, the most common usage of heaters in the Pacific Northwest appears to be in conjunction with other methods such as wind machines or as border heat (two to three rows on the upwind side) with undertree sprinklersystems.

The use of heaters requires a substantial investment in money and labor. Additional equipment is needed to move the heaters in and out of the orchards as well as refill the oil "pots". A fairly large labor force is needed to properly light and regulate the heaters in a timely manner. There are usually 30-40 heaters per acre although propane systems may sometimes have as many as 50. A typical, well-adjusted heating system will produce about 4.2 million BTUs per hour.

Based on the fact that "many small fires are more effective than a few big fires" and because propane heaters can usually be regulated much easier than oil heaters, propane systems often have more heaters per acre but operate at lower burning rates (and temperatures) than oil systems. It is sometimes necessary to place extra heaters under the propane supply tank to prevent it from "freezing up".

Smoke has never been shown to offer any frost protection advantages, and it is environmentally unacceptable. The most efficient heating conditions occur with heaters that produce few flames above the stack and almost no smoke. Too high a burning rate wastes heat and causes the heaters to age prematurely. The general rule-of-thumb for lighting heaters is to light every other one (or every third one) in every other row and then go back and light the others to avoid puncturing the inversion layer and letting even more heat escape. Individual oil heaters generally burn one-half to three-fourths of a gallon of oil per hour.

Propane systems generally require little cleaning, however, the individual oil heaters should be cleaned after every 20-30 hours of operation (certainly at the start of each season). Each heater should be securely closed to exclude rain water and the oil should be removed at the end of the cold season. Oil floats on water and burning fuel can cause the water to boil and cause safety problems.

Escaping steam can extinguish the heater, reduce the burning rate and occasionally cause the stack to be blown off.

The combination of heaters with wind machines not only produces sizeable savings in heater fuel use (up to 90%), but increases the overall efficiency of both components. The number of heaters is reduced by at least 50% (down to 10 to 20/ac) by dispersing them into the peripheral areas of the wind machine's protection area. Heaters should not be doubled up and are not usually necessary within a 150-200 foot radius from the base of the full-sized machine. Heat which is normally lost by rising above the tree canopy may be mixed back into the orchard by the wind machines. At the same time heat is also added from the inversion. The wind machines are turned on first and the heaters are used only if the temperature continues to drop.

Wind Machines

The first use of wind machines was reported in the 1920's in California, however, they were not generally accepted until the 1940's and '50's. They have gone through a long evolutionary process with a wide range in configuration and styles. Everyone of these designs has probably appeared in the Pacific Northwest at one time or another.

Wind machines, or "fans" as they are often called, are used in many orchard and vineyard applications. It is estimated that they are currently used on more than 150,000 acres in Washington orchards and vineyards. Some are moved from orchards after the spring frosts to vineyards to protect the grapes against fall frosts.

Wind machines, large propellers on towers which pull vast amounts of warmer air from the thermal inversion above an orchard, have greatly increased in popularity because of energy savings compared to some other methods and they can be used in all seasons. Wind machines provide protection by mixing the air in the lowest parts of the atmosphere to take advantage of the large amount of heat stored in the air. The fans or propellers minimize cold air stratification in the orchard and bring in warmer air from the thermal inversion. The amount of protection or temperature increase in the orchard depends on several factors. However, as general rule, the maximum that the air temperature can be increased is about 50% of the temperature difference (thermal inversion strength) between the 6- and 60-foot levels. These machines are not very effective if the inversion strength is small (e.g.., ≤ 2°F).

Wind machines that rotate horizontally (like a helicopter) and pull the air down vertically from the inversion rely on "ground effects" (term commonly used with helicopters, etc.) to spread and mix the warmer air in the orchard. In general, these designs have worked poorly because the mechanical turbulence induced by the trees greatly reduces their effective area. In addition, the high air speeds produced by these systems at the base of the towers are often horticulturally undesirable.

The current "standard" is a stationary vertical fan that are usually powered by gasoline or liquid propane engines that produce about 130 HP at 2400 rpm. The two 19 (5.8 m) blades rotate at about 590 rpm producing 800,000-1,000,000 ft^3/min (400 to 475 m^3/s) mass air flow. Improved blade design and the use of space age materials in their construction have resulted in major performance improvements in recent years.

A general rule is that about 12-15 BHP is required for each acre protected. A single, large machine (100-160 BHP) can protect up to 10 to 12 acres (4.5 ha) or a radial distance of about a 375-400 ft (120 m) under calm conditions. The height of the head is commonly about 34-36 feet (10-11 m) in height in orchards and vineyards. Lower blade hub heights for shorter crops is generally <u>not</u> advantageous since warmer air in the inversion still needs to be mixed with the cold surface air. Propeller diameters range from 12-19+ feet (3.6-5.8+ m) depending on machine age and engine power ratings. The propeller assembly also rotates 360° about its vertical axis every 4-5 minutes parallel to the ground. The blade assembly is oriented with approximately a 6° downward angle for maximum effectiveness over an area.

Modern machines rely on the principle that a large, slow-moving cone of air to produce the greatest temperature modification is the most effective (propeller speed of about 590-600 rpm). A non-vertically rotating wind machine has an effective distance of about 575-600 ft (180 m) without wind. The amount of air temperature increase decreases rapidly (as the inverse of the square of the radius) as the distance from the fan increases. In actuality, the protected area is usually an oval rather than a circle due to distortion by wind drift with the upwind protected distance about 90-100 m and the downwind distance about 130-140 m. Several wind machines are often placed in large orchard or vineyard blocks with synergistic benefits by carefully matching the head assembly rotation direction with spacing.

In response to the chronic need to increase cold temperature protection capability, several attempts have been made over the past 40 years to design or adapt wind machines so that the wind plume would distribute large quantities of supplemental heat throughout an orchard. These efforts have been uniformly unsuccessful. The high temperatures (e.g., 1300-1350°F [750°C]) of the added heat caused the buoyant air plume to quickly rise above the tops of the trees and mixing with the colder orchard air was minimal. These designs have ranged from "ram jets" on the propeller tips to the use of large propane space heaters at the base of the wind machine. The added heat actually causes the jet to quickly rise above the tops of the trees and substantially decreases the radius of the protected area due to the increased buoyancy of the wind plume.

Wind machines apparently work quite well when used in conjunction with other methods such as heaters and undertree sprinkling. They should <u>never</u> be used with overtree sprinkling for frost protection. If they are used by themselves, bare soil may be somewhat beneficial.

If you are planning on installing a wind machine, you'll need detailed information on inversions in your locale. You may want to put up a "frost pole" or tower to measure the temperatures with height in your orchard during springtime inversions. The machine should be located only after carefully considering the prevailing drift patterns and topographic surveys. Wind machines may also be located so as to "push" cold air out of particularly cold problem areas.

Helicopters. Helicopters are an expensive (and sometimes dangerous) variation of a wind machine which can also be used under radiation frost conditions. They can be very effective since they can adjust to the height of an inversion and move to "cold spots" in the orchard. The amount of area protected depends on the thrust (down draft) generated by the helicopter. Generally, the heavier (and more expensive) the helicopter, the better their protection capability. A single large machine can protect areas greater than 50 acres in size under the right conditions. However, due to the large standby and operational costs, the use of helicopters for frost protection is limited to special cases or emergencies.

Helicopters should work from the upwind side of the orchard making slow passes (5-10 mph). One technique which is used with helicopters is to have thermostatically controlled lights in problem areas which turn on at a preset cold temperature. The helicopter then flies around the block "putting out the lights". There should also be two-way radio communications between the plane and the ground. A rapid response thermometer in the helicopter helps the pilot adjust the flying height for best heating effect.

Other Frost Protection Techniques

The current trend for using oil and gas heaters for frost control appears to be in conjunction with other methods such as wind machines or as border heat (two to three rows on the upwind side) with undertree sprinklersystems. Burning tires, prunnings, wood, and other debris to assist the sprinklerirrigation systems is not a good idea. Smoke has never been shown to offer any frost protection advantages, and it is environmentally unacceptable. These fires are generally extremely inefficient and very little heat is provided to the orchard.

The use of chemical sprays (e.g. zinc, copper, antitranspirants, etc) to improve frost "hardiness" of deciduous trees in the Northwest has been found to offer no measurable benefit in limited scientific investigations. Likewise, sprays to eliminate "ice nucleating" bacteria have not been found beneficial because of the great abundance of "natural" ice nucleators in the bark, stems, etc. which more than compensate for any lack of bacteria. Special "fogging" systems which produce a dense 20-30 foot thick fog layer have also not worked well because of the difficulty in containing and/or controlling the drift of the fogs and potential safety/liability problems if they crossed a road.

Frost Monitoring Techniques

Traditionally, growers have relied on the National Weather Service frost forecasting programs (no longer available) and local forecasts which provide an indication of expected low temperatures and dew points. Many are now using consultants and subscribing to specialized forecasting services with mixed results. The use of the forecast data plus frost alarms and a good network of orchard thermometers are essential parts of each orchardist's frost protection program.

Reliable electronic frost alarm systems are available that alert the grower if an unexpected cold front has moved into the area. These systems can ring your telephone from remote locations, sound an alarm or even start a wind machine or pump. The sensor should be placed in a regular orchard thermometer shelter and its readings correlated with orchard thermometers which have been placed around the block(s) to set the alarm levels (after considering the critical bud temperatures). It is important that you have enough thermometers to tell you what is actually happening in your blocks.

Thermometer height depends on orchard training and density and should be placed at the lowest height where protection is desired. Thermometers may be lower in high density blocks with small trees and higher in more traditional orchards. Thermometers and alarm systems should be checked and recalibrated each year. Thermometers should be stored upright inside a building during the non protection seasons.

Windbreaks

Windbreaks are often used for aesthetic purposes, to reduce effects of prevailing winds or to divide blocks with little or no thought about their frost protection consequences. The proper use and placement of tree windbreaks and other barriers (buildings, roads, etc)to air flow in orchard frost protection schemes is very important. The placement of barriers may be beneficial or extremely harmful. It must be considered in the total orchard planning in frost prone areas.

Cold air movement during radiative conditions can often be visualized as similar to molasses flowing down a flat surface--very viscous, thick and slow. Anything that retards this flow causes a corresponding increase in the upstream cold air depths by as much as 4 to 5 times.

Cold air can be dammed or diverted like any other fluid flow. Consequently, it is possible to minimize cold air flows through an orchard, reduce heat losses (advective) and heating requirements with proper siting of these obstructions. Conversely, improper locations can greatly increase frost problems.

Windbreaks, buildings, stacks of bins, road fills, fences, tall weeds, etc. all serve to retard cold air drainage and can cause the cold air to pond in the uphill areas behind them. The size of the potential cold air pond will be at least equal to the contour at which the elevation of the "dam" intersects the hillside behind the obstruction. The effective cold air depth will most likely be greater than the height of a solid physical obstruction, depending on the effectiveness of the dam or diversion. (Diversions will likely have lesser depths than dams.) Tree windbreaks are porous and the extent of the potential damage is less predictable.

The basal area large tree windbreaks at the downstream end of the orchard should be pruned (opened) to allow easy passage of the cold air. Windbreaks at the upper end should be designed and maintained to minimize air entry (if there is not an orchard block above them) and, if possible, divert the cold air to other areas, fields, etc. that would not be harmed.

Summary and Conclusions

Overtree sprinkling can provide the highest level of frost protection of any of the methods used, if the application rates are sufficient and uniform. It is also the only technique that does not rely on the inversion layer for its effectiveness, and it is the only method that can provide some protection under advective conditions (with some risk, however!). Disadvantages of the method include the very large water requirements, ice loadings and severe damage potential in the event of water a application system failure. In addition, they cannot be used in winter cold protection activities. Use of water for frost protection in *V. vinifera* blocks is usually not recommended because of the need to carefully manage soil water levels (under canopy sprinkling is usually not an option).

Wind machines or "fans" rely totally on the strength of the temperature inversion for their effectiveness in warming the orchard. The large propeller pulls warmer air from higher layers in the inversion and mixes it through the orchard. This removes the cold air boundary layers around the buds/leaves and replaces it with warmer air. They can also be used to push cold air out of an orchard or vineyard. The placement of multiple wind machines must be carefully coordinated to maximize the areal extent and net effectiveness. Wind machines have been found to work well with properly placed orchard heaters and undertree sprinkling.

Heating by undertree sprinklers depends on mixing heat into the layer of air that includes the trees by convection. It is very dependent on the strength of the air temperature inversion above the canopy which limits the height of the heated volume. The level of heating is also dependent on the amount of water applied. A 1°F to as much as a 3°F temperature increase up to 12 ft in height can be expected under most radiative frost situations. The temperature of the applied water is quite significant in determining the protection level, and pre-heating water may be an option when adequate water supplies are limiting. They can also not be used in winter cold protection activities.

Microsprinklers can be used under the tree canopy for low temperature modification in orchards if the application rates are sufficient to provide enough heat. Research data indicate that the small droplet sizes with microsprinklers have no measurable benefit over properly operated impact heads. Any undertree design which applies the water as uniformly as possible is beneficial. Likewise, cultural practices such as cover crops which increase the freezing surfaces are also useful.

Application rates which are suitable for undertree or overtree sprinkling can be obtained with properly designed microsprinklers systems, but may not be economical. Our investigations show that the commonly published values of 0.08-0.10 in/hr (35-45 gpm/ac) for undertree and 0.15-0.18 in/hr (65-80 gpm/ac) for overtree systems are appropriate lower limits for water applications. Obtaining adequate water for reasonable levels of frost protection is a major grower concern.

Research has shown that equivalent undertree heating can be achieved at low application rates by the use of warm ground water or water that has been heated by solar heating or the use of a fossil fuel fired-heat exchanger. The use of a heat exchanger to warm water prior to application through existing undertree sprinkler systems offers major benefits. Heat is relatively uniformly and applied at low temperatures, which when coupled with reduced buoyancy effects compared to high temperature heater systems, more heat is retained within the orchard boundaries. In addition, with a fossil fuel fired-heat exchanger, heat input can be quickly adjusted to match environmental conditions at a single point. The use of a fossil fuel-fired heat exchanger can also provide significant savings in fuel costs compared to oil fired heaters for equivalent heating. Air pollution is also substantially reduced with a fossil fuel-fired heat exchanger based frost protection system. Low application rates conserve water and also reduces water logging of orchard soils and reduces leaching of nutrients and other chemicals towards the groundwater. Low application amounts are a major benefit on heavy soils.

The use of natural or artificial windbreaks needs to be carefully considered in planning for orchard and vineyard frost protection. It is quite common to find that these barriers to air flow are causing substantial damage in adjacent blocks of trees or vines because of poor placement and maintenance.

APPENDIX A

BASIC CONCEPTS AND DEFINITIONS

There are some basic climatological and physical definitions which should be understood. Some of these are:

Dew Point Temperature: The temperature at which condensation of the water vapor in the air first occurs. (This is one of the most powerful frost protection "systems" available!)

Wet Bulb Temperature: The minimum temperature obtained by a moist, evaporating body. Usually slightly higher than the dew point.

Ambient Temperature: The general temperature of the air mass in the orchard.

Latent Heat of Fusion: The heat released by water when it changes from a liquid to a solid (ice). 144 BTU/lb of water.

Latent Heat of Condensation: The heat released by water when it changes from a gas to liquid. 1076 BTU/lb of water at 32°F.

Latent Heat of Vaporization (Evaporation): The heat required (taken from whatever source is available) to evaporate water. If this heat comes from the air it causes "evaporative cooling" and this phenomena occurs even below 32°F! Equal to but opposite of the **latent heat of condensation** where the heat is released at the point of condensation.

Conduction: The transfer of heat within a body or from one body or fluid in direct contact with another.

Convection: The natural (circulation) or forced mixing of a fluid or gas to transfer heat to another fluid or gas.

Advection: Transfer of heat from one fluid or gas to another fluid or gas by horizontal mixing.

Radiation: The transmission of heat through space from a warmer to a cooler body in a straight line.

Inversion: A layer of warm air floating over a layer of cold air next to the ground surface. The temperature profile is coldest next to the soil surface and increases (almost linearly) to some distance above the ground. For frost protection purposes, inversion strength is often taken as the temperature difference between 6 and 60 feet although the temperature may still increase above that level. The greater the temperature difference, the greater the inversion strength. A 1-2°F difference is weak, a 3-6°F difference is moderate and a difference above 6°F is considered a strong inversion.

Critical Temperature: The critical temperature is defined as the temperature at which buds and/or other plant tissues (cells) will be killed.

Washington State University has published a series of single page sheets in color that are quite helpful in determining the approximate critical bud temperatures at any particular stage of growth for several deciduous fruit crops. Information on ordering these and other WSU Extension publications can be found in **Appendix B** at the end of this paper.

Types of Frost

There are basically two dominant types of frost situations which will be encountered. These are radiant frosts and advective freezes, although both types will usually be present in any spring (or fall) frost event.

<u>Radiation Frosts</u> A radiation frost is probably the most common during "cold sensitive" times in Washington and is the easiest to protect against. Almost all frost protection systems/methods available today are designed to protect against radiant-type frost/freezes. Radiant frosts occur when large amounts of clear, dry air move into an area. There is almost no cloud cover at night. During these times, the plants, soil, and other objects which are warmer than the very cold sky will "radiate" their own heat back to space and become colder and colder. In fact, the plants cool (radiate) themselves to the point that they can cause their own damage! The plant tissues which are directly exposed to the sky become the coldest.

These radiation losses (as much as 1-1.5 million BTU/ac/hr) can cause the buds, blossoms, twigs, leaves, etc. to become 2-4°F colder than the surrounding air which radiates very little of its heat. The warmer air then tries to warm the cold plant parts and it also becomes colder. The cold air settles toward the ground and begins a laminar flow towards lower elevations. This heavier, colder air moves slowly ("drifts") down the slope under the influence of gravity (technically called "katabatic wind"), and collects in low areas or "cold pockets". This drift can also carry a considerable amount of heat out of or into (from higher elevation heating activities) an orchard or vineyard.

The general rate of temperature decrease due to radiative losses can be fairly rapid until the air approaches the <u>dew point temperature</u> when atmospheric water begins to condense on the colder plant tissues (which reach atmospheric dew point temperature first because they are colder). The <u>heat of condensation</u> is directly released at the point of condensation, averting further temperature decreases (at least temporaily). Thus, the exposed plant parts will generally equal air temperature when the air generally reaches dew point. At the dew point, the heat released from condensation replaces the radiative heat losses and further air temperature decreases will be small and occur over longer time periods. A small fraction of the air will continue to cool well below the general dew point temperature and drift down slope.

Thus, having a general dew point near or above critical plant temperatures to govern air temperature drop is important for successful, economical frost protection programs (which is, fortunately, often the case). Economically and practically, most cold temperature modification systems must rely on the heat of condensation from the air. This huge latent heat reservoir in the air can provide great quantities of free heat to an orchard or vineyard. Severe plant damage often occurs when dew points are below critical plant temperatures because this large, natural heat input is lacking and our other heating sources are unable to compensate. There is little anyone can do to raise dew points of large, local air masses.

Concurrent with the radiative processes and in the absence of winds, a thermal inversion condition will develop where the temperature 50 to several hundred feet above the ground may be as much as a 10-12°F warmer than air in the orchard. Springtime temperature inversions in central Washington will often have a 3-5°F temperature difference (moderate inversion strength) as measured between 6 and 60 feet above the surface. Many frost protection systems such as wind machines, heaters and undertree sprinkling rely on this temperature inversion to be effective.

<u>Advective Freezes</u> Advective freezes occur with strong, cold (below freezing), large-scale winds persisting throughout the night. They may or may not be accompanied by clouds and dew points are frequently low. Advective conditions do not permit inversions to form although radiation losses will still happen. The cold damage is caused by the rapid, cold air movement which conducts or "steals" away the heat in the plant. There is very little which can be done to protect against advective-type freezes.

However, it should be pointed out that winds at above freezing temperatures greater than about 3-4 mph are beneficial on radiative frost nights since it keeps the warmer, upper air mixed into the orchard, destroying the inversion and replaces radiative heat losses.

APPENDIX B

WSU Extension Publications Related to Frost Protection

Bulletin	Title	Cost
EB 0913	Critical temperatures for blossom buds - apples	$0.25
EB 0914	Critical temperatures for blossom buds - peaches	0.25
EB 0978	Critical temperatures for blossom buds - pears	0.25
EB 1128	Critical temperatures for blossom buds - cherries (sweet)	0.25
EB 1186	Critical temperatures for blossom buds - prunes	0.25
EB 1240	Critical temperatures for blossom buds - apricots	0.25
EB 0634	Frost and frost control in Washington orchards	0.50

Order from: Bulletin Department,
WSU Cooperative Extension,
Cooper Publications Building
Washington State University,
Pullman, WA 99164-5912

Note: Minimum orders less than $10 are not accepted so it may be advisable for several people to go together and order sufficient quantities.